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14. ABSTRACT
Here, load carriage interventions for walking *energy expenditure* and *running speed* have been designed to: 1) advance existing models and 2) contribute needed data to the broader effort to develop load-carriage decision-aid tools for modern soldiers. We hypothesize first that our height, weight (including load), speed, and grade algorithms proposed will allow walking metabolic rates to be predicted to within 6.0 and 12.0% in laboratory and field settings, respectively. We hypothesize second that the speed-load carriage algorithms will allow load-induced decrements in all-out sprint running speeds to be predicted to within 6.0% in both laboratory and field settings. Respective load-carriage algorithms for *walking energy expenditure* and *running speed* will be developed and tested (Technical Objectives 1.0 and 2.0) in the laboratory and the field.

15. SUBJECT TERMS
gait, metabolism, performance, load carriage

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INTRODUCTION

The Need for Load Carriage Decision-Aid Tools

Load carriage is a foot-soldier requirement with direct consequences for a broad array of physiological, performance and health outcomes. Metabolic energy expenditure, heat production, macronutrient requirements, water requirements, and injury risks are all directly elevated by the weight of the equipment soldiers carry while both short- and long-term mobility are substantially reduced (Knapik et al., 1996; Knapik et al., 2004). Clearly, the physiological stresses and mobility losses induced by load carriage do not constitute desirable field outcomes. Indeed, anecdotal (Knapik & Reynolds, 2010) and formal (Dean, 2004) accounts of the negative consequences of pack overloads are readily available from a multitude of field combat situations. In both modern and historical warfare environments alike, the physiological status and mobility of foot soldiers influence combat performance, wound and survival rates. Accordingly, exacting considerations of the value of carried equipment evaluated against the negative performance, wound and mortality consequences of added weight are a matter of vital military importance.

A priori, one might expect that the major advances in both material science and electronics in the modern era would provide soldiers with more effective equipment while simultaneously reducing the loads soldiers carry. However, the historical record indicates a marked trend in the opposite direction. During the 150-year period from the Civil War through the present day, the pack weights of American foot soldiers have *increased* by a factor of approximately 3-fold, from 15 kg during the Civil War to 35 kg in World War II to approximately to 45 kg in Desert Shield (Knapik & Reynolds, 2010), and 45 kg or above in Afghanistan (Dean, 2004). For an average-sized male US soldier, a load of 45 kg constitutes well over 50% of the body's weight. Thus, the theoretical potential for technological advances in equipment and materials to lighten the pack and total body loads carried by modern foot soldiers has not been realized.

This brief consideration of the historical trends for the loads carried by US soldiers across different eras begs two immediate questions: are the loads carried by modern soldiers excessive? And if so, how harmful is the additional weight carried to warfighter performance?

This answer depends on a fundamental and long-standing load carriage trade-off assessment that balances the *benefits of the equipment carried* vs. the *detrimental performance consequences* imposed by carrying additional weight. On a qualitative level, the benefits of modern body armor, firepower, and communication equipment are relatively obvious, as are the negative physiological and mobility consequences of carrying heavy loads. However, at present, the data needed for quantitative, evidence-based considerations are unavailable. Consequently, well-informed decisions about the pack and total body loads that will be most effective for soldiers in operational environments are not possible.

Given that warfighter field effectiveness is crucial to the efforts of the US military, moving beyond qualitative considerations of the load carriage cost-benefit trade-offs constitutes minimum due diligence to the soldiers in the field as well as to the enormous national investment in our military initiatives. The work proposed here will contribute to a broader experimental work effort to develop **load-carriage, decision aid tools** that take an evidence-based approach to determining loads for foot-soldiers. The specific experimental work we propose focuses on the cost, or detriment side of the load carriage trade-off equation. This work is expected to provide

data that are currently lacking, but necessary for informing strategic decisions regarding pack and total load carriage weights.

We present a series of experiments designed to quantify the negative physiological and performance consequences of the loads modern soldiers carry. The work has been formulated using two promising physiological-mechanical models: 1) a stature-based model to explain walking energy expenditure, and 2) a ground force model to explain brief, all-out running speeds. Fulfilling our experimental objectives should allow predictions of the specific physiological, performance and mobility decrements that would be expected across a broad continuum of potential loads.

Objective One: Walking Energy Expenditure

Previous Scientific Efforts of Direct Military Relevance: Because metabolic rates are so fundamentally related to physiological status and sustained performance capabilities, the Army has a long-standing interest in developing techniques to predict and monitor the metabolic rates of soldiers walking in the field. As with most efforts to acquire or predict physiological data in field environments, this has proven to be a challenging undertaking. However, modern monitoring capabilities and improved predictive modeling should allow for meaningful progress.

The pioneering efforts of Pandolf and others in the 1970's (Givoni & Goldman, 1971; Pandolf et al., 1977) established generalized equations that predict the metabolic rates of walking soldiers from total weight (i.e. body weight + load), speed and grade. However, the utility of these equations depends heavily on the ability to acquire walking speed and grade data in the field. This ability was formerly quite limited, but in recent decades has become fully feasible and highly accurate.

In part, because the ability to monitor speed and distance in field environments limited the original applicability of the Pandolf et al. equations, other approaches were pursued. In the 1990's, Hoyt and colleagues (Hoyt et al., 1994; Hoyt & Weyand, 1996; Hoyt et al., 2004; Weyand et al., 2001) adopted an innovative technological approach that, in contrast to the Pandolf approach, did not require speed and distance data. Hoyt devised a bio-monitoring strategy to predict locomotor metabolic rates from the body's weight and the periods of foot-ground contact. This approach was inspired by algorithms (Kram & Taylor, 1990) that explained the metabolic rates of different-sized terrestrial running and hopping animals. Hoyt and colleagues successfully developed biosensors that accurately monitored ambulatory foot-ground contact times and predicted metabolic rates under some conditions (Hoyt et al., 1994; Hoyt et al., 2004; Weyand et al., 2001). However, this approach was not without limitations. Foot-ground contact monitoring requires a functioning sensor and a wireless network, and current monitors cannot detect the surface inclinations that have a substantial effect on walking energy expenditure (Margaria et al., 1968; Minetti et al., 1994; Minetti et al., 2002).

Modeling Walking Metabolism: Recently, we have developed a promising model for predicting walking metabolic rates that combines the strengths of the Pandolf and Hoyt approaches that can be readily implemented in the field using the accurate geo-location systems now available.

Our model may advance predictive accuracy beyond that provided by the two generalized models most commonly used to estimate the metabolic rates of human walkers at present: the Pandolf

and American College of Sports Medicine (ACSM) equations. Both use *body weight* and *walking speed*, but not *stature* to predict metabolic rates. Although comparative physiologists have long recognized (Alexander, 1976; Taylor et al., 1982; Kram & Taylor, 1990) that the mass-specific metabolic cost of locomotion varies in a systematic manner with the linear dimensions of the body, the leading models for predicting locomotor costs of humans have not incorporated body or leg lengths. The inverse relationship between the body's length (i.e., height) and the mass-specific metabolic rates of individual human walkers has been recently demonstrated (Weyand et al., 2010)

The Stature-Based Model of Walking Metabolism: Our new stature-based model of walking energy expenditure (Weyand et al., 2010) includes three fully independent variables: body mass, stature and walking speed. The quantitative form of the model is as follows:

$$E_{metab} = RMR + C_1 \cdot RMR + C_2 \cdot V^e/Ht \qquad (eq. 1)$$
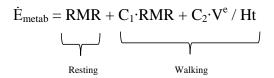
where E_{metab} is the body's total metabolic rate, RMR is resting metabolic rate, V is the velocity of walking, and Ht is height. C_1 and C_2 are empirically derived coefficients, and e is an exponent that quantifies equivalent walking velocities for individuals who differ in height. All metabolic rates in the equation are expressed in mass-specific terms.

In our model, RMR is the body's minimum or baseline rate of energy expenditure, the quantity $(C_1 \cdot RMR)$ represents the factorial increase above resting metabolic rate needed to maintain a walking posture (i.e. a postural metabolic rate, or PMR), and the term $(C_2 \cdot V^e/Ht)$ describes the curvilinear, or exponential, increase in mass-specific metabolic rates that occurs with increases in walking velocities standardized to height in accordance with the original suggestion of Alexander (Alexander, 1976; Alexander, 2003) to use the Froude Number (= V^2/gravity $\cdot$ leg length). The product of our slightly modified (for utility and convenience) model term V^e/Ht, and the coefficient C_2, represents the metabolic energy expended to lift, support and accelerate the body's center of mass with each step as walking speed is increased.

Two critical assumptions were involved in our development of the stature-based model to predict walking metabolic rates. First, we assumed that the mass-specific **metabolic energy expended per stride is the same at equivalent walking speeds** regardless of the height and weight of the individual. Second, we assumed that individuals who differ in stature **walk in a mechanically similar way at equivalent walking speeds** (i.e. the same Froude Number or value of V^2/Ht). Here, mechanical similarity is defined as stride lengths and times being related by a constant proportion across individuals of different heights.

Extending the Stature-Based Model to Load Carriage and Graded Walking:

Load Carriage: Two aspects of the model seem promising with respect to extending the stature-based model to the load carriage conditions: the predictive accuracy of the model on the independent and heterogeneous subjects evaluated so far, and a clear conceptual and quantitative basis from which to predict the effect that loading will have. Per below, our stature-based model breaks total walking metabolism into resting and walking components.

$$\dot{E}_{metab} = RMR + C_1 \cdot RMR + C_2 \cdot V^e / Ht$$

Resting   Walking

Because the relationship between the weight supported and both of the walking, or non-resting component of our model is 1:1, the predictions of the model for the effect of loading are straightforward: loading will increase the *walking* portion of the total metabolic rate in direct proportion to the load added. Thus, a load equal to 10% body's weight will increase walking metabolic rates by 10%; a load equal to 20% of body's weight will increase walking metabolic rates 20%, etc.

While there is a relatively large body of literature on the consequences of loading for walking metabolism (Bastien et al., 2003; Das & Saha, 1966; Duggan & Haisman, 1992; Falola et al., 2000; Griffin et al., 2003; Holewijn, 1990; Martin & Nelson, 1986; Pimental & Pandolf, 1979), none of the studies available provide the data needed to evaluate the predictive accuracy of the stature-based model under these conditions. Two quantitative issues prevent this: existing data sets and models have not included the influence of stature on walking metabolism, and previous studies have not quantified or reported resting metabolic rates that can be quantitatively related to the resting <u>and</u> postural terms in our model. However, the best data available for evaluating our model (Griffin et al., 2003) indicate that loading results in gross walking metabolic rates being elevated slightly less than in direct proportion to load, while net walking rates (subtracting a standing value) are elevated in slightly greater than 1:1 proportion are consistent with our model predictions.

Graded Walking: Similarly, our expectation is that our model will also apply to graded walking, although per above, quantitative evaluations of our model using the existing literature (Margaria, 1968; Minetti et al., 1994; Minetti et al., 2002; Wanta et al., 1993) are not possible. For graded walking, our approach will be to extend our findings of a constant metabolic cost per stride at equivalent speeds for different individuals to inclined and declined conditions. Under level walking conditions, we found that the lower mass-specific metabolic rates of taller vs. shorter individuals are fully explained by differences in body lengths (i.e. height) and proportional differences in the horizontal distance traveled with each stride (i.e. stride length). Extending our stature-based model to explain metabolic rates during inclined and declined walking involves similar quantification of the distance traveled by the body during each stride. During horizontal walking, including only the horizontal displacements is sufficient. During graded walking, our stature-based model predicts metabolic rates will be a function of both the *horizontal* and *vertical* displacements of the body over the course of each stride. Stride lengths during graded walking are expected to be proportional to stature at equivalent walking speeds as during horizontal walking. However, the vertical displacements of the body over the course of each stride will be a function of <u>both</u> the surface grade and stature. Per intuition, the vertical distance per stride traveled will be greater on any inclined or declined walking surface for taller vs. shorter individuals. Accordingly, metabolic rate deviations from the level condition for taller vs. shorter individuals are also expected to be greater on any given incline or decline. Mechanically, this is most easily conceptualized as the metabolic cost per stride increasing and decreasing in accordance with the positive and negative displacements of the body during each stride. This metabolic pattern is well described in the comparative literature for large and small animals (Taylor et al., 1972), but the data needed to assess humans of different statures is unavailable.

Our expectation is that we can use stature and percent grade to quantify this effect. In the specific terms of our model, our expectation is that our coefficient, C_2 that describes the increases in metabolic rate in relation to increases in equivalent walking speeds, will have the same value for any given positive or negative vertical displacements of the body per stride. Although this relationship will need to be determined empirically, we can make the simple prediction that the value of C_2 during inclined and declined walking will be proportional to the product of the stature of the individual and the percent grade of the surface (i.e. $C_2 \propto Ht \cdot \%$ grade).

The experiments proposed here represent the most fundamental empirical steps needed to extend and validate our stature-based model. Once the basic work needed to develop algorithms including load, incline and decline conditions has been completed, additional work to incorporate the effects of fatigue (Epstein et al., 1988; Patton et al., 1991), terrain (Pandolf et al., 1977) and very steep downhill grades (Margaria, 1968; Santee et al., 2001) may then be explored in the context of the model.

Objective Two: Sprint Running Speed

Previous Scientific Efforts: The scientific literature on the basis of brief, all-out running performance is far less extensive than that devoted to the energy cost of walking. Early efforts focused primarily on explaining performance in terms of the metabolic power available for these events (Hill, 1925; Hill, 1950; Ward-Smith, 1985; Ward-Smith, 1999; Ward-Smith, 2000). While some investigators have continued to use metabolic models to explain these performances (Rittweger et al., 2009), the predominant scientific focus has shifted to mechanical models (Bundle et al., 2006; Usherwood & Wilson, 2005; Usherwood & Wilson, 2006, Chang & Kram, 2007; Weyand et al. 2000; Weyand et al., 20006; Weyand et al., 2010) to explain sprint exercise performances. In our view, this shift is scientifically warranted as mechanical approaches can directly explain the motion of the body and promising force models using this approach are being developed (Weyand et al., 2006; Weyand et al., 2010). In contrast, metabolic models continue to be difficult to validate at present due to the ongoing inability to quantify the whole-body anaerobic and total metabolic energy released during sprinting (Bangsbo, 1998; Van Pragh, 2007).

For the purposes of predicting sprint exercise performance here, we have opted to quantify load-induced decrements in speed as fractional decrements from the unloaded condition. Our interpretation of the existing literature indicates that this approach is likely to provide the greatest predictive accuracy from a simple, practical model. There are at least two sound, literature-based reasons for adopting this approach. First, maximal sprint performances vary considerably between individuals for physiological and mechanical reasons that are incompletely understood and likely cannot be modeled simply. Second, the relationship between all-out sprint running speeds and the average ground forces applied during each step, both within and across individuals, is reasonably linear during sprint running (Weyand et al., 2000; Weyand et al., 2010) which simplifies model predictions.

We expect to be able to predict load-induced decrements in speed with a high degree of accuracy because loads are not likely to alter the maximum forces runners can apply to the ground, but will predictably increase the ground force required to run at any speed. Accordingly, we should be able to use a runner's force maximum at his or her unloaded sprinting speed maximum, load-

induced increases in the ground forces required, and the general force-speed relationship to predict load-induced decrements in all-out speed.

Our speed model takes the simple following form:

$$V_L = C_1 \bullet (L/W_b) \bullet V_{UL} \hspace{4cm} \text{(eq. 2)}$$

where V_L is the maximum velocity of loaded running for all-out runs of brief duration, W_b is body weight, L is the weight of the load carried, C_1 is the coefficient describing the load-induced decrements in speed resulting from fractional additions to the body's weight (L/W_b) via loading, and V_{UL} is the maximum velocity of running in the unloaded condition.

Our force-speed model has its basis in both basic Newtonian mechanics and the ground force capabilities of individual runners. An extensive body of scientific evidence supports the view that a primary mechanical requirement of running is supporting the body's weight against gravity. Successful characterizations of running energetics and even speed and distance monitoring have been realized from this conceptual starting point (Kram & Taylor, 1990; Weyand et al., 2001). Our force-speed model also begins with this basic recognition.

The mechanical basis of our empirically-formulated force model of sprint running is most easily understood by considering how the ground contact and aerial phases of a running stride change across speed for individual runners. The relative durations of the aerial and foot-ground contact phases of a running stride vary with speed. As runners increase their speeds, they spend relatively more time in the air and relatively less time on the ground. Consequently, the ground support forces that runners apply increase in an approximately linear fashion with speed and are set by body mass. For runners regardless of ability, stance-averaged ground support forces are 1.5 times the body's weight while jogging, and increase to 2.0 times the body's weight or more when running at sprinting speeds.

Here, we expect that loading will result in proportional increases in the stance-average ground reaction forces required with little effect on the time course of ground force application. This result has also been reported from studies examining loaded running at slower speeds (Chang & Kram, 2000). The consistency observed in the foot-ground contact times at any given speed across different loads suggests that our general approach is sound

Beyond this, we have found that the limit to running speed occurs when runners reach that speed at which they are repositioning their limbs as quickly as possible while simultaneously applying maximum ground forces. Contrary to intuition, the minimum times runners require to reposition their limbs at their top running speeds does not vary in relation to how fast they can run. Consequently, individual differences in speed are explained all but entirely by the mechanics of the stance phase. These mechanical observations support a modeling approach that focuses on the ground force required and available for speed.

At present, firm predictions of the decrements in brief, all-out running speeds that will occur with loading and that will be quantified by the coefficient C_1 in our force-running speed model are difficult. This is the case because only small number of studies to date have examined the effects of loading on sprint running performance (Alcaraz et al., 2008; Cronin et al., 2008; Holewijn & Lotens, 1992). The few studies that do present loaded and unloaded all-out sprinting speed data

do so under conditions that make more generalized predictions difficult, and none of these studies include the ground reaction force data. The most informative study with respect to our experimental objectives here is that of Holewijn & Lotens (1992) who reported that a load equal to 21% of body weight reduced all-out running velocities by 13 and 18% for all-out 80- and 400-meter runs. More recently, Alcaraz et al. (2008) reported only 3% reductions in brief, all-out running speeds with loads equal to 9% of the body's mass, while Cronin et al. reported fractional reductions in all-out loaded sprinting speeds that were approximately half as large as the fractional increases in load/body weight ratios. The disparity in the different results reported to date could result from a large number of factors, and is therefore difficult to interpret. These empirical results project a C_1 value in our model somewhere between 0.4 and 1.0.

Fractional reductions in brief, all-out running speeds that are, in some cases only half as large as the fractional loading of the body's weight reported are surprising. The relatively shallow slope of the force-speed relationship portends a much greater sensitivity. The mechanistic factors that explain a much more limited effect than would be theoretically expected from unloaded force-speed data only are almost certainly rooted in the mechanics of the stance phase ground force application that occurs under loaded conditions. These likely involve mechanical adaptations to loading that improve the leverage of the limb (Biewener et al., 2004) and thereby reduce the muscle forces required in relation to the load being carried.

However, in the complete absence of ground reaction force data or the accompanying video data to determine limb leverage, speculating about the adjustments that may constrain load-induced decrements in speed is difficult. The limited existing data available point to a critical need to acquire ground reaction force and video data under a variety of load and duration conditions to develop a robust predictive model. These data should provide the key to understanding how musculoskeletal mechanics, loading strategies, training and conditioning strategies, and conceivably external aids like exoskeletons, may be utilized to minimize detrimental losses in the short-term mobility of soldiers that result from carrying heavy loads.

BODY

The majority of the first calendar year of the award was devoted to the submissions to multiple review authorities to acquire approval for testing human subjects. Final approval was granted in late December of 2012. The first four months of the 2013 calendar year have been devoted to experimental set-up, experimental design, protocol development and refinement, and subject recruitment. As the first year of the award closed, experimental preparations and protocol refinement were largely concluded and we were poised to begin data collection in accordance with the objectives and approach below:

The load carriage experiments have two specific objectives: 1) to develop and validate algorithms that predict walking metabolic rates from height, weight (including load), speed and grade, and 2) to develop and validate algorithms that predict brief, all-out running speeds from the body and pack weights of the individual. These objectives will be pursued in parallel per the following experimental timeline.

<u>Objective 1 – Walking Energy Expenditure</u>:

We intend to acquire energy expenditure data in the laboratory on those subjects on whom our predictive metabolic equations will be developed using our stature-based model. Subjects will complete walking trials at a number of different walking speeds treadmill grades while their rates of oxygen uptake and energy expenditure are measured.

We will also complete the aforementioned laboratory walking trials across speed and grade needed for our original subjects as needed for algorithm development. In addition, we will undertake field data acquisition by having subjects will undergo a field march on a surveyed field course of known elevations and grades while instrumented to acquire the metabolic and position data.

<u>Objective 2 – Sprint Running Speed</u>:

We will first conduct high-speed running tests in the laboratory on subjects under three different loading conditions: unloaded, +15% body weight, and +30% body weight. Subjects will complete protocols to determine their maximum speeds for efforts ranging from 2 to 90 s while force and video data are acquired.

Next, we will acquire all-out overground running data in both indoor and outdoor settings on subjects. These subjects will complete 25 meter runs indoors and 60 meter runs outdoors under four different loading conditions: unloaded, +15% body weight, +30% body weight, and +45% body weight. Simultaneous force and video data will be acquired during the indoor 25-meter running trials.

KEY RESEARCH ACCOMPLISHMENTS

Per above the first two quarters of the year were devoted to acquiring human subjects approvals and putting the physical space and testing infrastructure in place to execute the experiments proposed. Key accomplishments through the first 9 months of the grant year were as follows:

1) LabVIEW software was developed for our force plate data acquisition system, video trigger, synchronization and user interface.
2) Instrumentation was finalized on the force plate data acquisition system.
3) HRPO approval of our human use protocol was provided on December 20, 2012.
4) We completed a laboratory expansion and renovation required for the proposed work. The expanded, renovated area includes 600 square feet of additional laboratory and office space. The expansion allows our existing space to now accommodate bilateral testing.
5) Installation of a new treadmill and metabolic system to be used in testing was completed. On-site tests were performed with an outside engineer to validate new and existing metabolic systems.
6) Pilot testing of the protocol sessions was undertaken to evaluate feasibility, duration and possible fatigue effects.

7) A search was initiated to fill a new research position to be supported by this award. We are in the final stages of making a recommendation to Human Resources and a request to hire.

In the most recent quarter, ending in April, our key accomplishments were as follows:

1) Completed pilot testing and consultations with USARIEM and other military personnel to determine the method of loading.
2) Purchased the weighted vests, backpacks, and loading materials needed to load subjects.
3) Designed the scaffolding support structure needed to decline our commercial treadmill in accordance with our protocol obligations.
4) Conducted pilot testing across speeds and inclines to inform final protocol decisions.
5) Hired and began training a research technician who will have a 100% obligation on this award. Our new technician researcher began on April 1st.
6) Acquired contact information for 15 to 20 individuals who qualify for inclusion in the study.
7) Hired a part-time research assistant to assist with data acquisition and testing who also recently began her employment and training.

REPORTABLE OUTCOMES

Reportable outcomes for the first nine months of the grant year were as follows:

1. Experimental and laboratory data acquisition preparations have been completed:
   - Laboratory expansion and renovation
   - Metabolic testing systems validated and relocated
   - Force plate data acquisition system completed and tested
2. Human subjects protocol was approved by the HRPO
3. The search process for a new researcher is nearing completion
4. Pilot testing is for finalizing test procedures is nearly finished

Reportable outcomes for the last quarter of the grant year were:

1. Pilot testing has been completed.
2. The testing protocol has been finalized.
3. Equipment and accessories preparation for subject testing is now complete. This includes treadmill foundation for declined conditions and backpack weighting equipment and methods.
4. Two new employees, one full-time and one part-time, have been hired and are now on staff
5. The science television Nova visited the laboratory on April 8th and 9th to shoot for an upcoming episode on human performance that is planned for national airing on PBS in October of 2013.

6. A theoretical/modeling manuscript on the force-motion model for running that will be further tested via this protocol has been prepared for submission to the journal *Biology Letters* of the Royal Society Publishing Group of the United Kingdom.

CONCLUSIONS

In the first year of the award, we completed the lengthy process of formulating a human subjects testing protocol and gaining approvals from the different reviewing authorities as required. We expanded our laboratory facilities, added personnel, added equipment, prepared new data acquisition systems, identified and purchased the footwear, vests and weighting materials needed and completed pilot testing of the experimental protocols.

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APPENDICES

None.